Atmospheric Radiative Transfer : UMBC models
Monochromatic and Fast Models
Clear sky Cloudy sky Non-LTE

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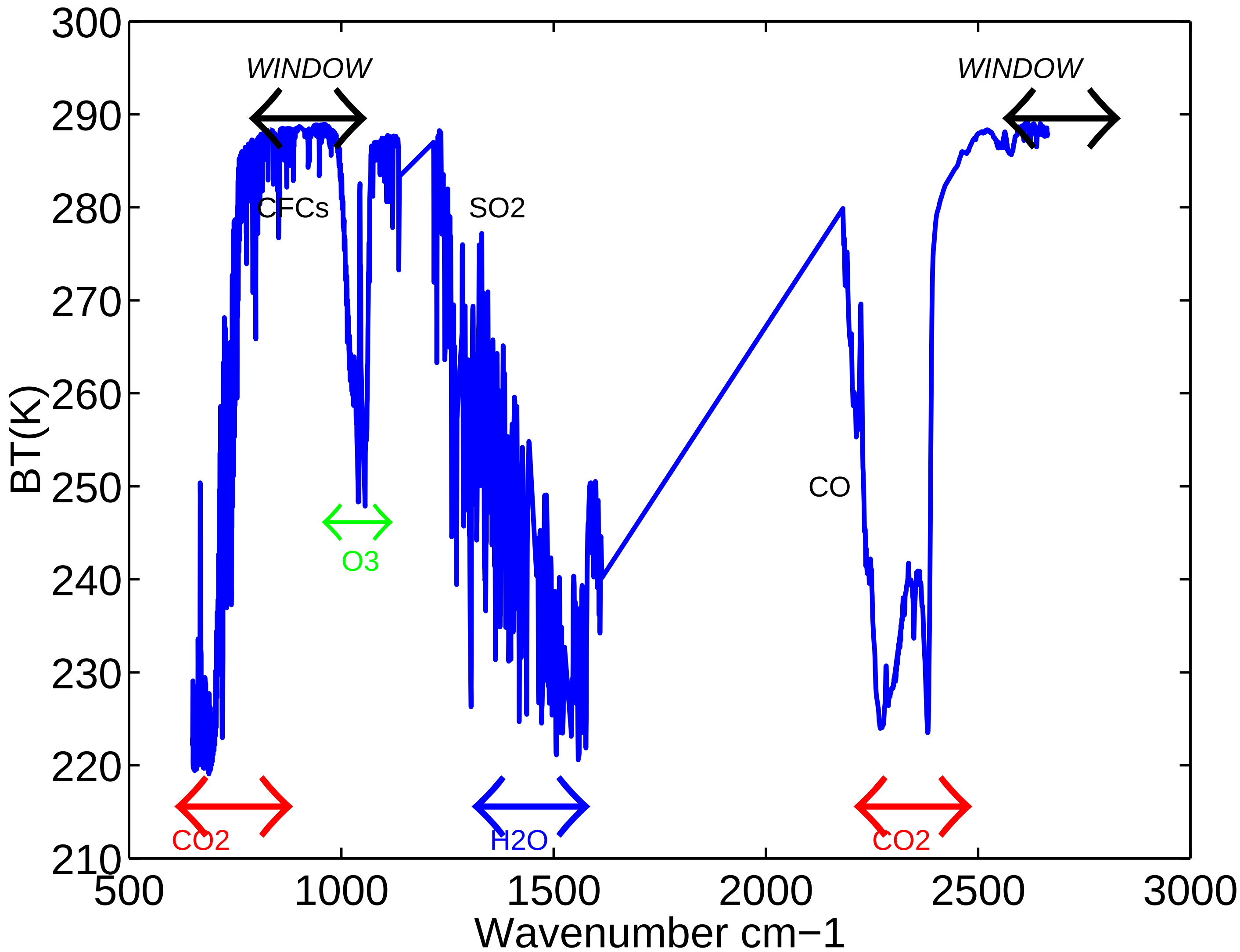
Overview

- Clear sky radiative transfer
- Fast Models
- Particle scattering
- Cloudy sky radiative transfer
- Non Local Thermodynamic Equilibrium

Brightness Temperature vs Wavenumber



Radiative Transfer

- At steady state, the 1D Schwartzchild Equation says

$$\mu \frac{dI(\nu,\theta)}{k_e dz} = -I(\nu,\theta) + J(\nu)$$

- $\mu = cos(\theta)$, dz is the vertical coordinate
- k_e is the total extinction (due to gases, clouds etc)
- $k_e dz = ds$ is the optical depth
- $I(\nu,\theta)$ is the radiance intensity
- J is the source function

- If $J = 0$, then simple solution shows attenuation as beam propagates

$$I(\nu,\theta)(z) = I_0(\nu,\theta)e^{-(k_e z/\mu)}$$

Source function J

- Clear Sky, in LTE : $J = B(\nu, T)$
- Clear Sky, in NLTE : $J = rB(\nu, T)$ r COMPLICATED
- Cloudy Sky, in LTE :

$$\mu \frac{dI(\nu)}{k_e dz} = -I(\nu) + B(\nu, T)(1 - \omega_0) + \frac{\omega_0}{2} \int_{-1}^{+1} I(\nu, k_e, \mu\prime) P(\mu, \mu\prime) d(\mu\prime) + \frac{\omega_0}{4\pi} \pi I_{sun} P(\mu, -\mu_{sun}) e^{-k_e z/\mu_{sun}}$$

- $\omega_0 = k_s/k_e = 1 - k_a/k_e$ is the single scattering albedo (0 for no scatter)
- $P(\mu, \mu')$ is probability of scattering from μ' into μ
- $P(\mu, -\mu_{sun})$ is probability of scattering from μ_{sun} into μ

Solution of Radiative Transfer Equation I : Clear Sky

- For Clear Sky, one layer only, the equation to be solved is

$$\mu \frac{dI(\nu,\theta)}{k_e dz} = -I(\nu,\theta) + B(\nu)$$

- the solution is

$$I(\nu,\tau_e) = I(\nu,0)e^{-s_e/\mu} + B(\nu,T)(1 - e^{-s_e/\mu})$$

- $I(\nu,0)$ is the incident radiation at bottom of layer
- $B(\nu,T)$ is the Planck radiance for the layer, at temperature T
- s_e is the total optical depth of the layer $= k_e Z$
- $\lim \tau_e \ll 1$ means $I(\nu,\tau_e) \rightarrow I(\nu,0)$ Surface Temperature
- $\lim \tau_e \gg 1$ means $I(\nu,\tau_e) \rightarrow B(\nu,T)$ Layer Temperature

Solution of Radiative transfer Equation I : Clear Sky (contd)

- For Clear Sky, one layer only

$$I(\nu,\tau_e) = I(\nu,0)e^{-s_e/\mu} + B(\nu,T)(1-e^{-s_e/\mu})$$

- Can iterate this for many layers (build up atmosphere)

$$\begin{aligned} I(\nu) \quad = \quad & \epsilon_s B(\nu,T_s)\tau_{s\to\infty}(\nu,\theta)+ \\ & \textstyle\sum_{i=1}^{i=N} B(\nu,T_i)(\tau_{i+1\to\infty}(\nu,\theta)-\tau_{i\to\infty}(\nu,\theta))+ \\ & I_{refl.thermal} + I_{solarbeam} \end{aligned}$$

- ϵ_s, T_s are the surface terms
- T_i are the $i = 1, N$ layer temperatures
- Solution is in many codes, such as KCARTA
- Quite fast code!!!!
- Accuracy tested by instrument campaigns (CAMEX, WINTEX) and AIRS

LBL Models and Instrument Retrievals

- kCARTA takes about 6 minutes to run for ONE radiance set
- Other LBL codes take about 1 hour to run
- New instruments eg AIRS have 2378 channels, 90 observations in 3 sec
- To do retrievals, we need a code that takes about 1 sec to run
- Instruments see the convolved monochromatic radiances
  $I_j(instr) = \int SRF_j(\nu)I(\nu)d\nu$

Fast Models - high resolution instruments eg AIRS

AIRS is a high resolution instrument with narrow spectral channels.
The upwelling monochromatic radiance (here τ is layer-space transmittance)

$$I(\nu) = \epsilon_s B(\nu, T_s)\tau_S + \sum_{i=1}^{i=N} B(\nu, T_i)(\tau_{i+1} - \tau_i)$$

needs to be convolved over the spectral channels.

$$\begin{aligned} I_j &= \int d\nu SRF(\nu)\epsilon_s B(\nu, T_s)\tau_S + \\ &\quad \textstyle\sum_{i=1}^{i=N} \int d\nu SRF(\nu) B(\nu, T_i)(\tau_{i+1} - \tau_i) \end{aligned}$$

Planck term and emissivity do not vary appreciably over the channel width and so can be taken out of the integral!

$$\begin{aligned} I_j &= \epsilon_s B(\nu, T_s) \int d\nu SRF(\nu)\tau_S + \\ &\quad \textstyle\sum_{i=1}^{i=N} B(\nu, T_i) \int d\nu SRF(\nu)(\tau_{i+1} - \tau_i) \end{aligned}$$

$$I_j = \epsilon_s B(\nu, T_s)\mathcal{T}_S + \sum_{i=1}^{i=N} B(\nu, T_i)(\mathcal{T}_{i+1} - \mathcal{T}_i)$$

SARTA replaces convolved monochromatic radiances with radiances generated from convolved transmittances

$$\mathcal{T}_i = \int d\nu SRF(\nu)\tau_i(\nu)$$

Fast Models - low resolution instruments eg MODIS

MODIS has wider spectral channels.

The upwelling monochromatic radiance (here τ is layer-space transmittance)

$$I(\nu) = \epsilon_s B(\nu, T_s)\tau_S + \sum_{i=1}^{i=N} B(\nu, T_i)(\tau_{i+1} - \tau_i)$$

needs to be convolved over the spectral channels.

$$\begin{aligned} I_j \quad = \quad & \int d\nu SRF(\nu)\epsilon_s B(\nu, T_s)\tau_S + \\ & \textstyle\sum_{i=1}^{i=N} \int d\nu SRF(\nu) B(\nu, T_i)(\tau_{i+1} - \tau_i) \end{aligned}$$

Planck term and emissivity vary appreciably over the channel width and so need to be treated more carefully!

Looking at one of the terms in the summation,

$$I_i(modis) \quad = \quad \int SRF(\nu) B(\nu, T_i)(\tau_{i-1} - \tau i) d\nu$$

if we assume

$$I_i(modis) \quad = \quad (\mathcal{T}_{i+1} - \mathcal{T}_i) B(\nu_{eff}, T_i)$$

we can find an effective planck frequency for each layer by solving for

$$B(\nu_{eff}, T_i) = \frac{I_i(modis)}{(\mathcal{T}_{i+1} - \mathcal{T}_i)}$$

Convolved transmittances

- Convolved transmittances modelled using a regression based approach
- Generate training set of convolved transmittances using (48) regression profiles, using kCARTA
- Solve for the coefficients that relate [convolved layer transmittance] with [profile based predictors], for each component gas and layer.

$$\mathcal{A}X = B$$

where A = (m $\times$ n) predictor matrix, X = (n $\times$ 1) coefficients, B = (m $\times$ 1) transmitance

Convolved transmittances (contd)

- Monochromatically, for g=1 to G gases the total transmittance is the product of the individual transmittances $\tau_{g1}\tau_{g2}\tau_{g3}...\tau_{gG}$
- This is not true after convolution!

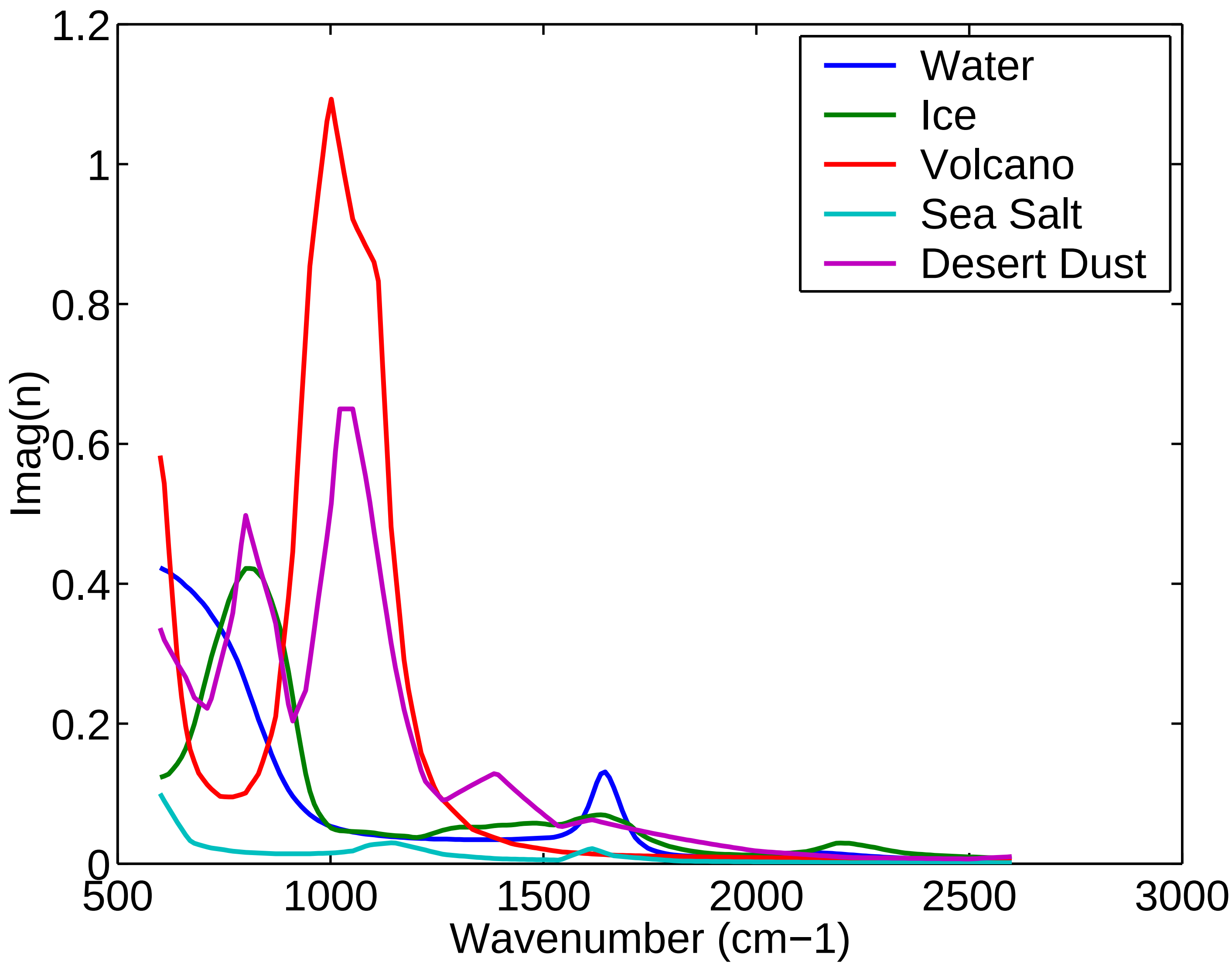
$$\int d\nu SRF(\nu)\tau_{g1}(\nu)\tau_{g2}(\nu) \neq \int d\nu SRF(\nu)\tau_{g1}(\nu) \times \int d\nu SRF(\nu)\tau_{g2}(\nu)$$

- But we can ratio convolved transmittances!!!! Let $\int d\nu SRF(\nu)\tau_{g1}(\nu)\tau_{g2}(\nu) = \mathcal{T}_{12}$ and $\int d\nu SRF(\nu)\tau_{g1}(\nu) = \mathcal{T}_1$ then the effective transmittance of gas 2 is $\mathcal{T}_{2eff} = \frac{\mathcal{T}_{12}}{\mathcal{T}_1}$
- "Break out" 5 gases (H2O,CO2,O3,CH4,CO), while other gases are kept "fixed" or constant (transmittance depends only on layer temperature)
- The variable gases are treated differently eg CO2 does not vary a lot, while water vapor varies by orders of magnitude.

General Comments

- Our models use P/R linemixing for CO2 (temperature sounding)
- Can also tweak the water vapor continuum
- Scott looked at thousnds of clear sky spectra to put in overall tweaks
- They certainly do not make expt data agree "less" with LBL codes
- Hidden complexities such as : reflected thermal, modelling solar contributions

Scattering particles in Atmosphere : Refractive Index



Scattering matter in atmosphere

Size considerations

- Typical infrared wavelengths λ : 3 - 15 um
- Typical dust particles $< r > \simeq$ 1-2 microns in radius
- Typical cirrus particles are larger ($< r > \simeq$ 10s of microns or more)
- If $\lambda \simeq < r >$ need to worry about scattering
- Mie scattering is easiest (spheres)
- Need to know $\Re, \Im$ parts of the refractive index

Look for far field solution ($d \gg r$), and obtain

- absorption optical depth τ_a
- scattering optical depth τ_s
- extinction optical depth $\tau_e = \tau_a + \tau_s$
- phase function $P(\theta)$ (prob of scattering into angle θ)
- asymmetry factor $g = \int P(\theta) cos\theta d\theta$

Scattering matter in atmosphere (contd)

- Standard codes exist for Mie scattering
- Average the above parameters over the distribution function
- Lognormal distributions, gamma distributions, realistic cirrus particle distributions etc
- Codes for NONSPHERICAL particles are complex. Anthony Baran of UKMO gave us parameters for ice aggregates, and hexagonal plates.

Solution of Radiative transfer Equation II : Cloudy Sky

- For Cloudy Sky, solution is much more complicated!
- AIRS is infrared instrument (solar does not kick in till SW)
- In the thermal window region (800-1200 cm-1 or 8-12 microns), $\tau_s \ll \tau_a$ can use absorptive code!!!!!
- In the SW window region (2400-2700 cm-1 or 3 microns), Worry about scattering, solar beam ($\tau_s \simeq \tau_a$)
- Solution by specialised codes, such as DISORT,RTSPEC
- Depending on complexity of solution, code can be quite slow!
- Concentrating on thermal IR, we wrote a kTWOSTREAM code which is fast, and compares excellently against DISORT, RTSPEC
- Get reflection R, transmission T, layer emission E and solar beam B coefficients for one layer; add together coeffs for many layers.

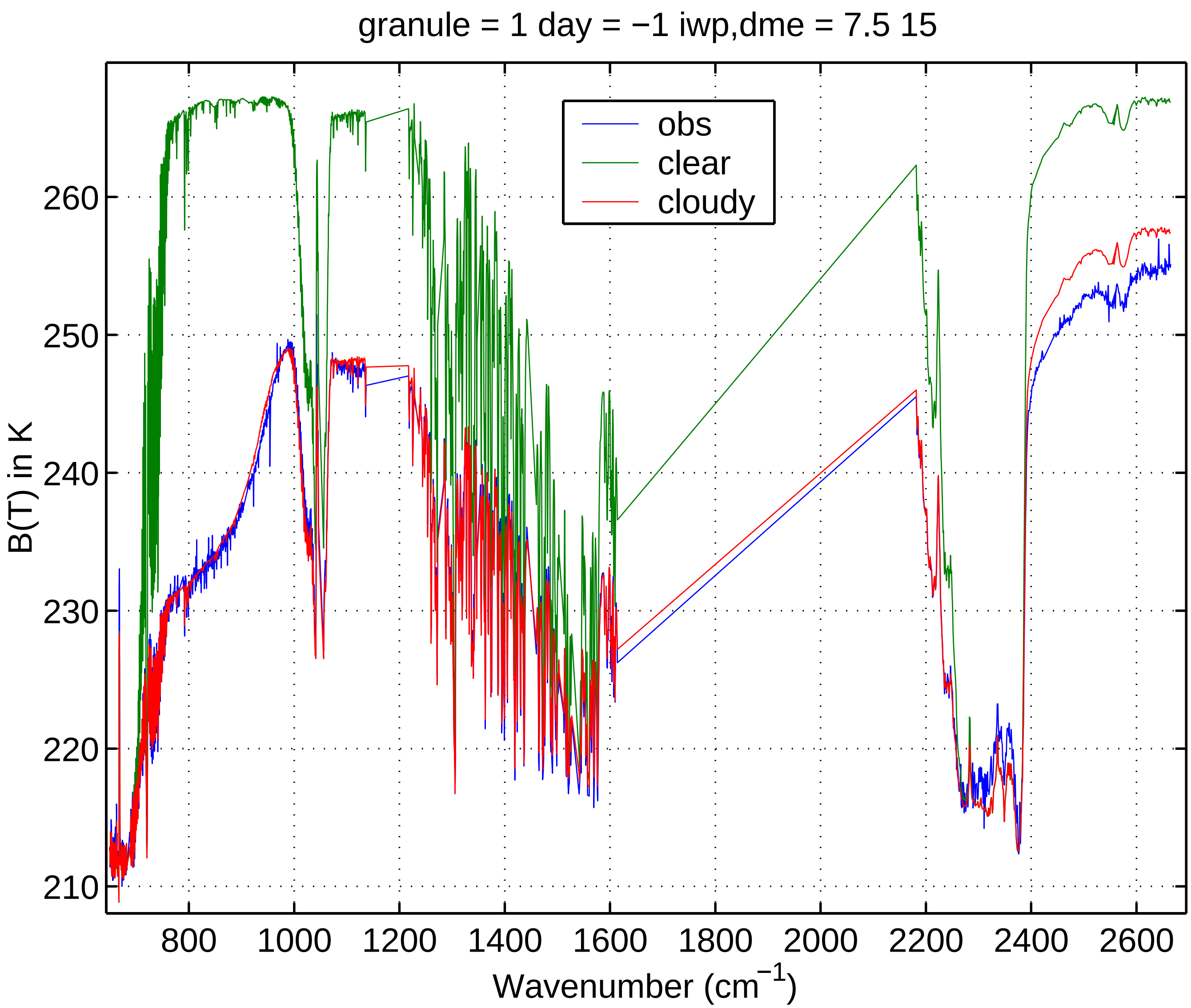
kTwoStream code

- Integrodifferential equation

$$\mu \frac{dI(\nu)}{k_e dz} = -I(\nu) + B(\nu, T)(1 - \omega_0) + \frac{\omega_0}{2} \int_{-1}^{+1} I(\nu, k_e, \mu\prime) P(\mu, \mu\prime) d(\mu\prime) + \frac{\omega_0}{4\pi} \pi I_{sun} P(\mu, -\mu_{sun}) e^{-k_e z/\mu_{sun}}$$

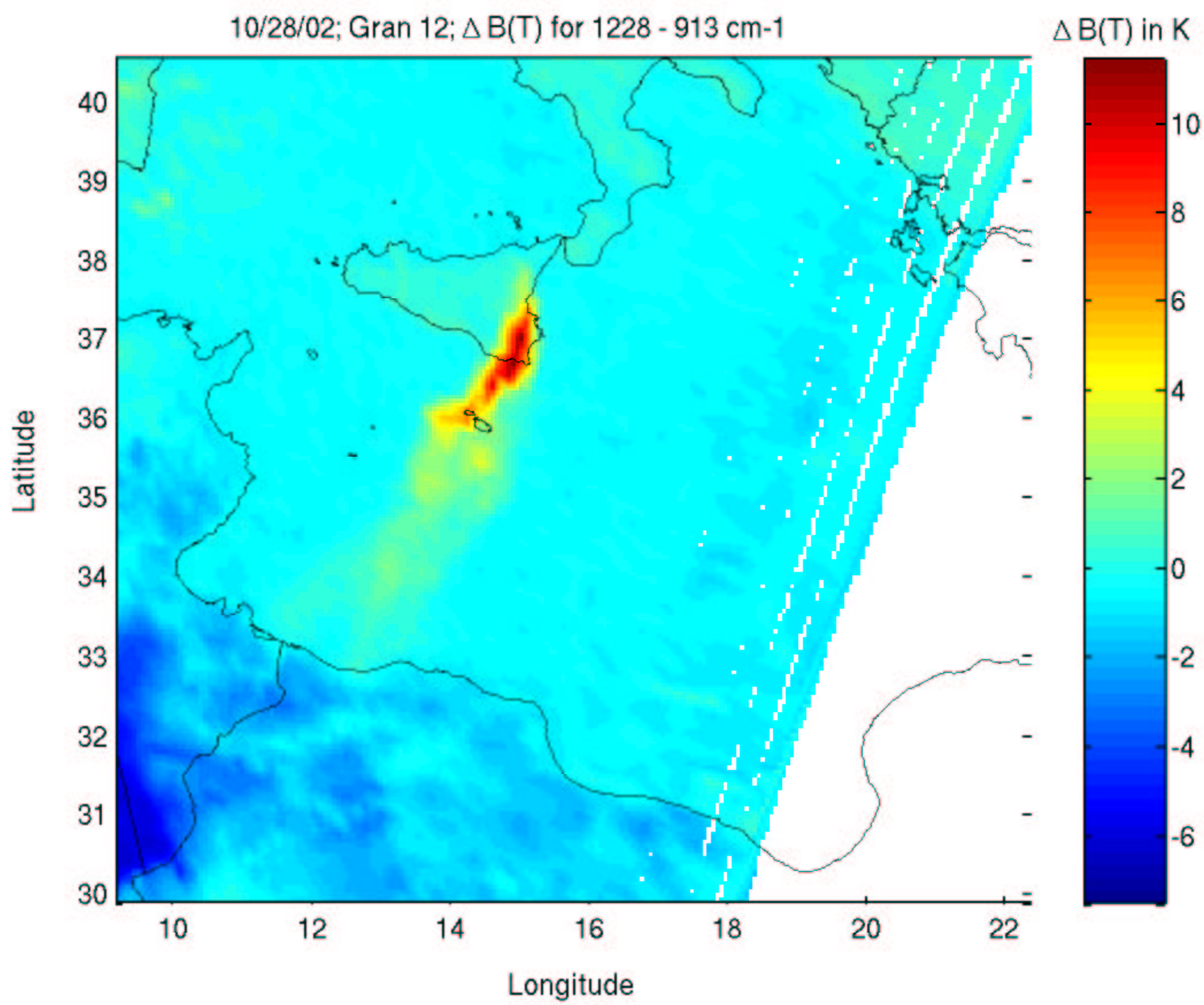
- Find the solution at N quadrature points; DISORT uses arbitrary number of streams; RTSPEC and TWOSTREAM use two (Gaussian) quadrature points, at $cos(\theta_{\pm}) = \pm 1/\sqrt{3}$
- having solutions for the two stream angles, we can get the solution at arbitrary angle, by integrating RTE

Cirrus Spectral Signature

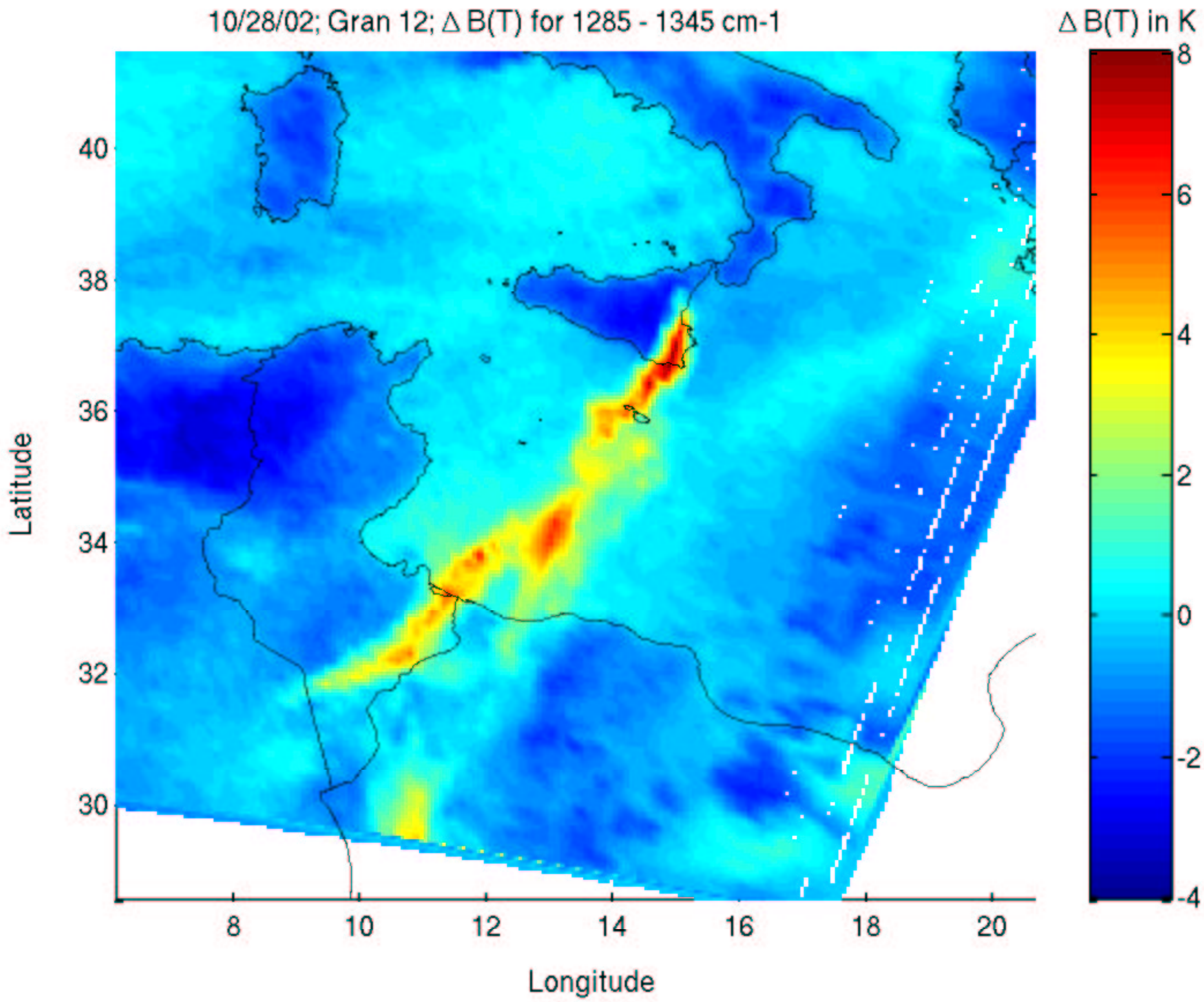


MODIS Image of Plume Mt Etna eruption

Aerosol Plume



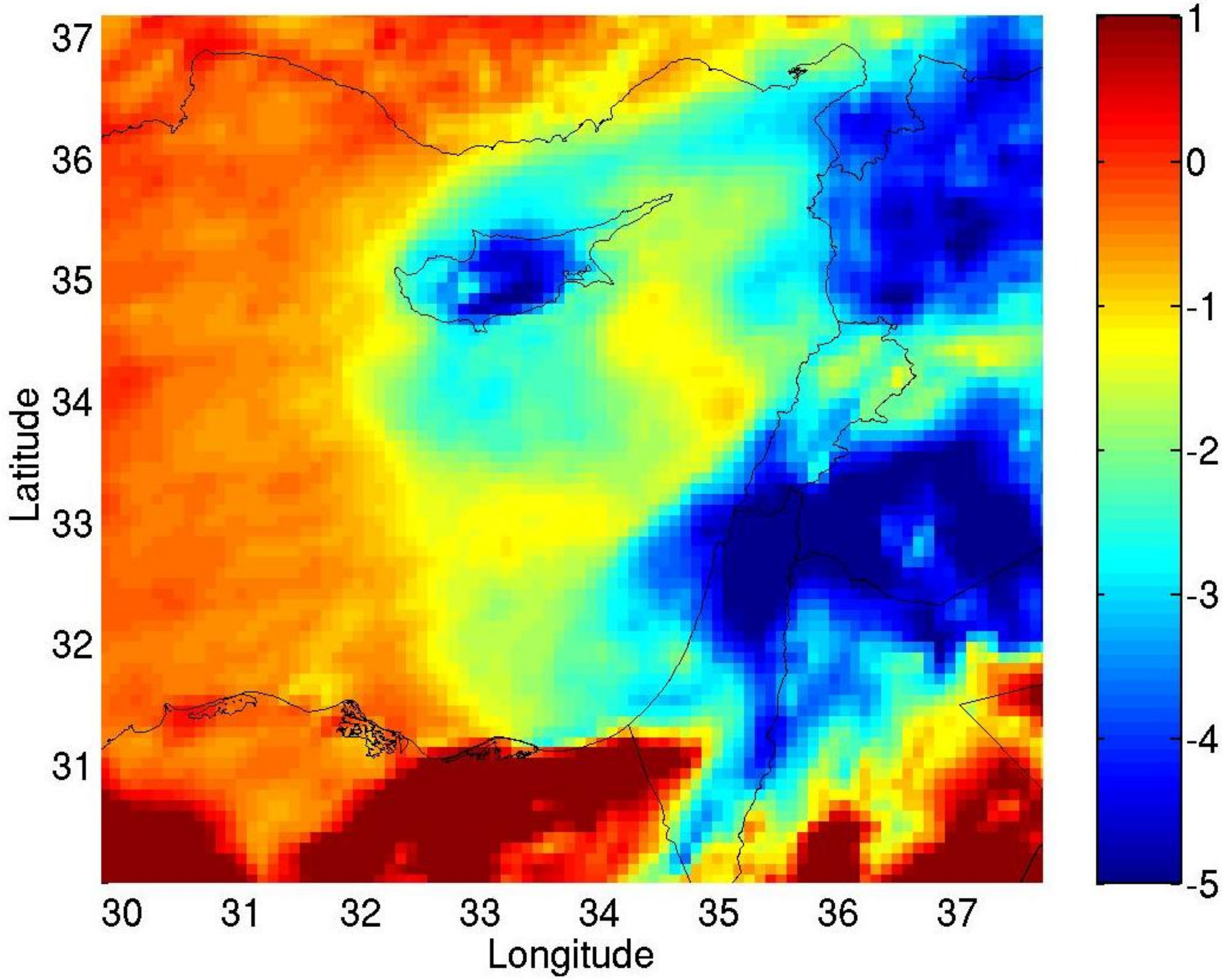
SO_2 Plume



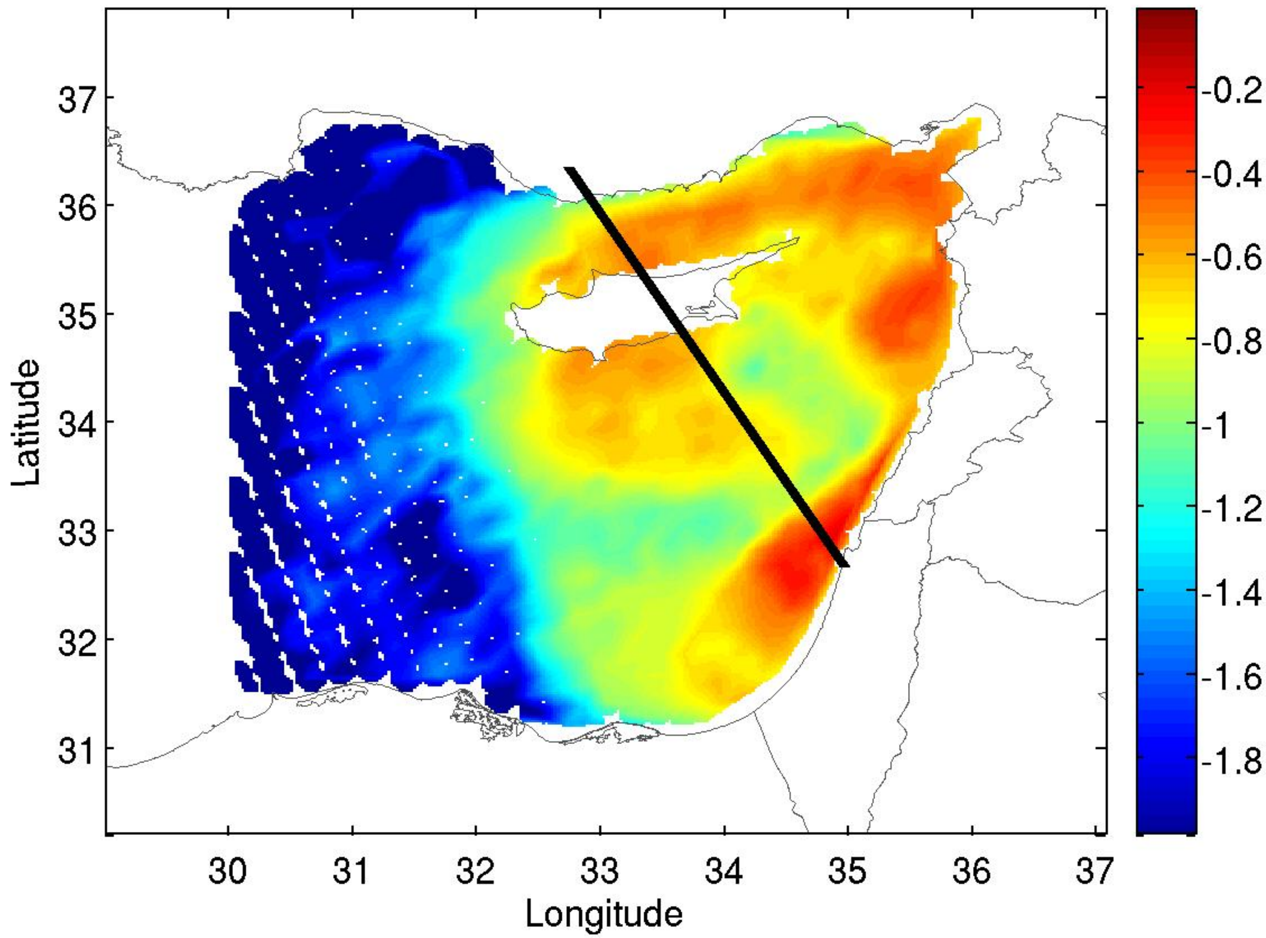
10/28/02; Gran 12; Δ B(T) for 1285 - 1345 cm-1
Δ B(T) in K
Latitude
Longitude
40
38
36
34
32
30
8
10
12
14
16
18
20
8
6
4
2
0
-2
-4

MODIS image for October 19, 2002 over E. Mediterranean

Using AIRS to detect dust : 960 - 1216 cm-1 BT diffs



Optical Depth retrieval



Solution of Radiative transfer Equation III : NLTE Sky

- Collisions tend to equilibriate temperatures
- Solar heating can preferentially pump some vibrational modes of certain gases, raising their temperature
- At high altitudes, very few molecules, so fewer collisions
- This means that some gases can be in Non Local Thermodynamic Equilibrium (NLTE) in the upper atmosphere
- The radiative transfer equation to be solved is now

$$\mu \frac{dI(\nu,\theta)}{k_{nlte} dz} = -I(\nu,\theta) + \beta B(T,\nu)$$

- need to compute β, k_{nlte}

Computing the optical depths

- T_l = local thermodynamic temperature of layer l,
- $T^{g,l}_{vib}(i)$ = NLTE vibrational temperature of the ith band, gas g at the same layer l.
- Vibrational band center denoted by ν_0
- $k^{g,l}(i,\nu_0)$ is the LTE absorption coefficient, $q^{g,l}$ is the gas amount in the layer

at NLTE the optical depth is related to the LTE optical depth by

$$k^{g,l}_{nlte}(i,\nu_0)q^{g,l} = k^{g,l}(i,\nu_0)\alpha^{g,l}(i,\nu_0)q^{g,l}$$

- $\alpha^{g,l}(i,\nu_0)$ is an adjustment factor
- As $T^{g,l}_{vib}(i) \rightarrow T_l$, $\alpha \rightarrow 1$

Computing the Planck modifier

- T_l = local thermodynamic temperature of layer l,
- $T^{g,l}_{vib}(i)$ = NLTE vibrational temperature of the ith band, gas g at the same layer l.
- Vibrational band center denoted by ν_0
- $k^{g,l}(i,\nu_0)$ is the LTE absorption coefficient, $q^{g,l}$ is the gas amount in the layer

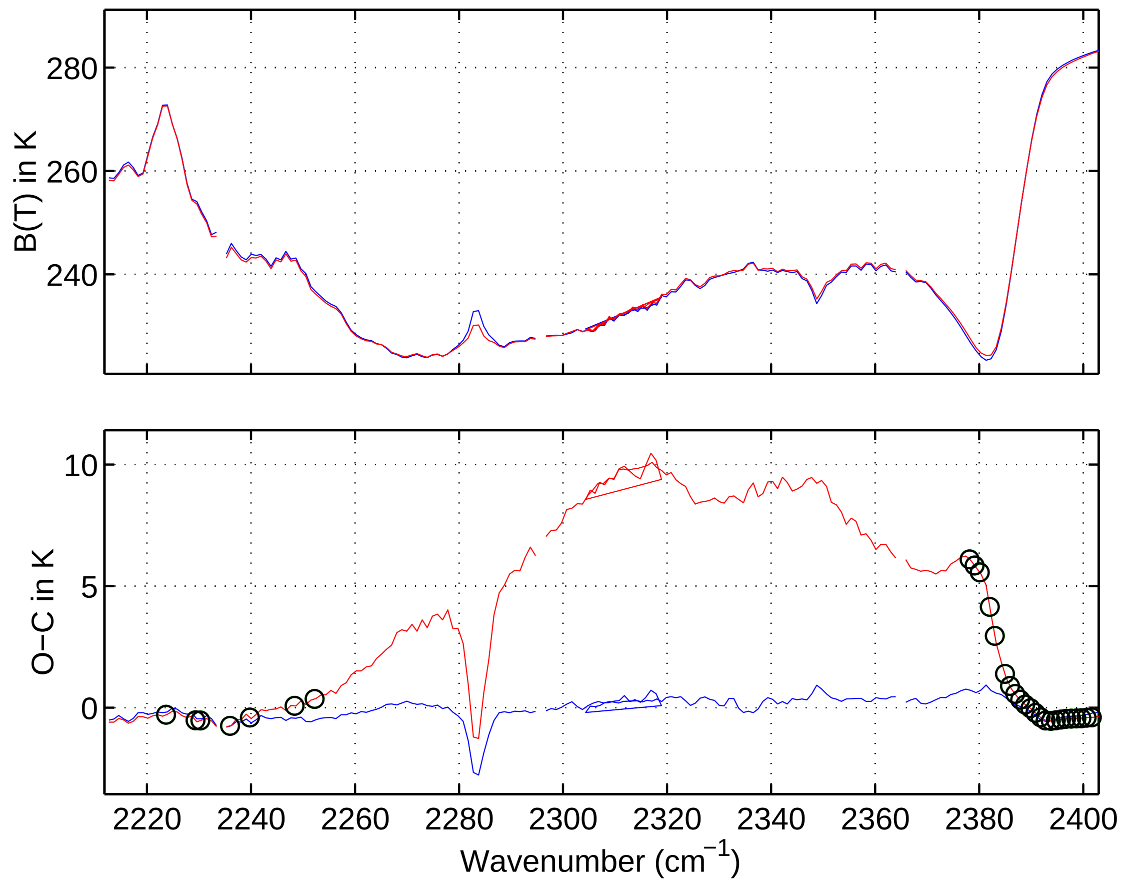
at NLTE the Planck function is related to the LTE planck function by

$$B^{T,T(g,l)}_{nlte} = B(T)\beta^{g,l}(i,\nu_0)$$

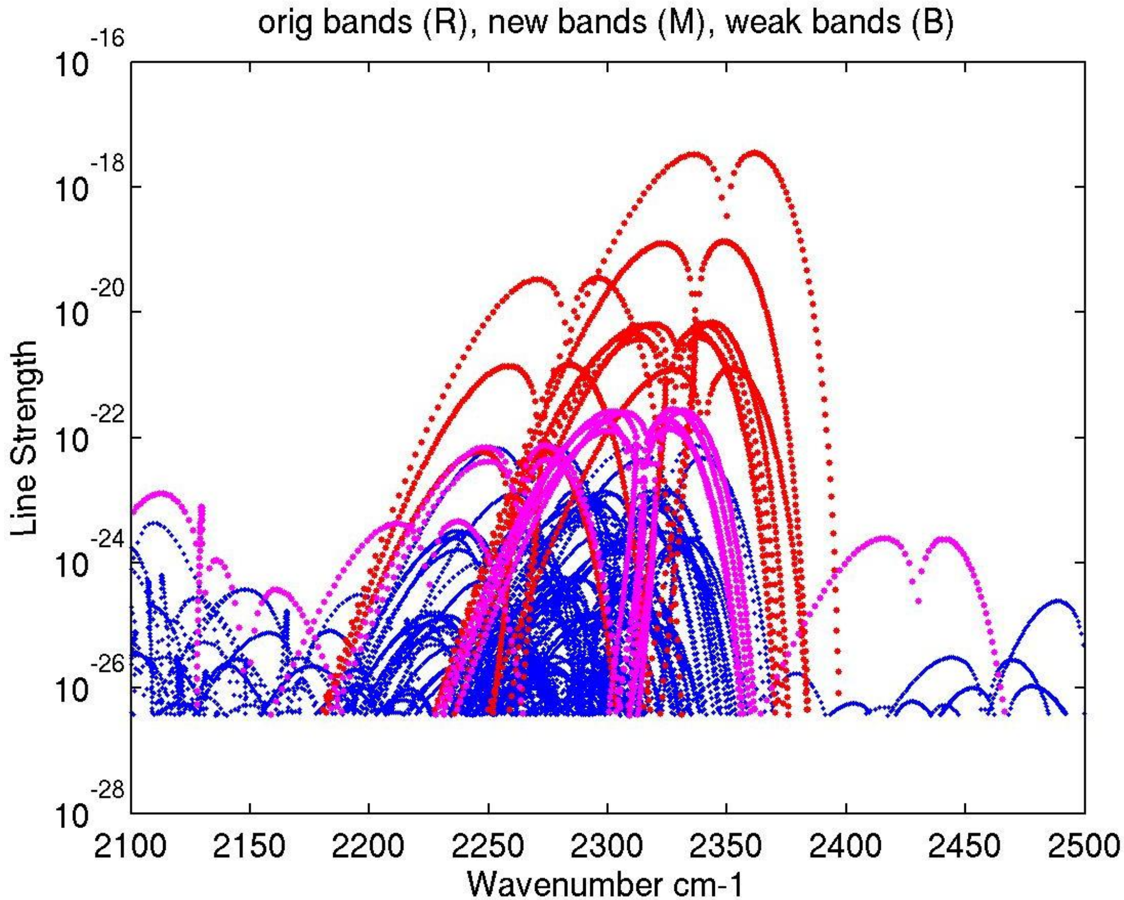
- $\beta^{g,l}(i,\nu_0)$ is an adjustment factor
- As $T^{g,l}_{vib}(i) \to T_l$, $\beta \to 1$

Effect on Non-LTE on Sounding Channels

NLTE affects some upper atmosphere AIRS channels that have been designated for temperature sounding

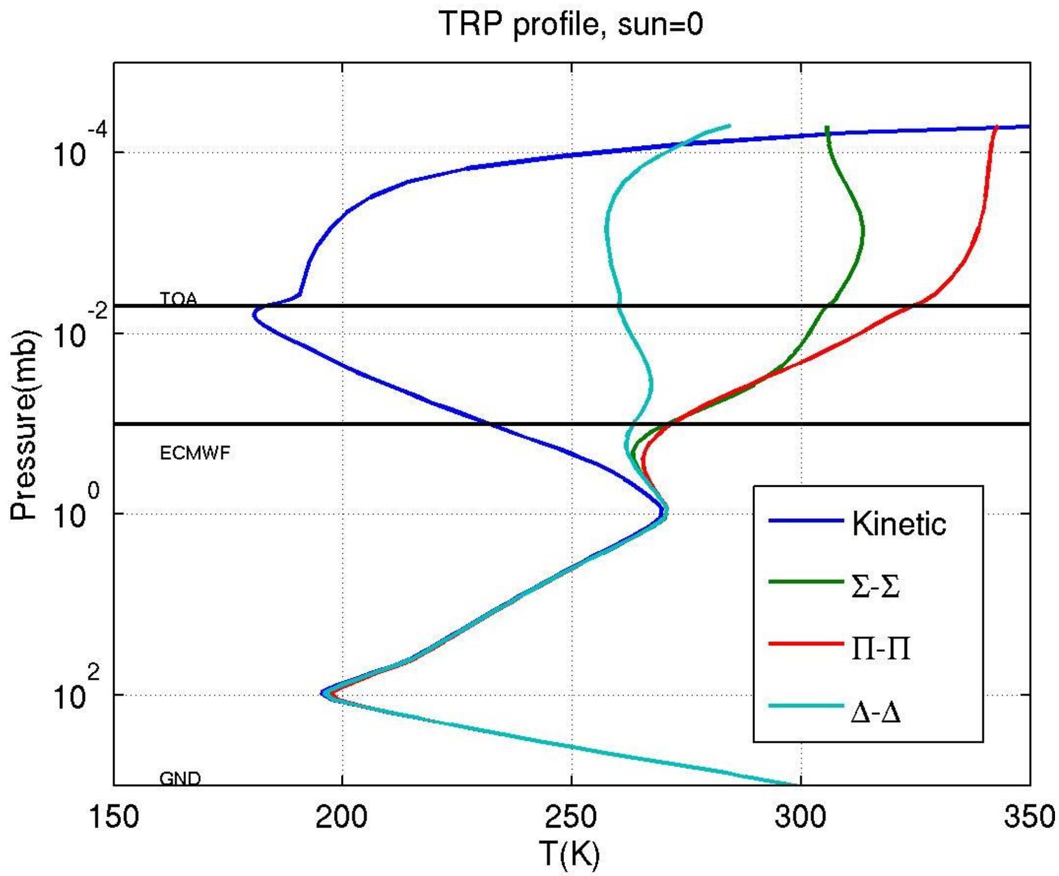


Bands used for NLTE model



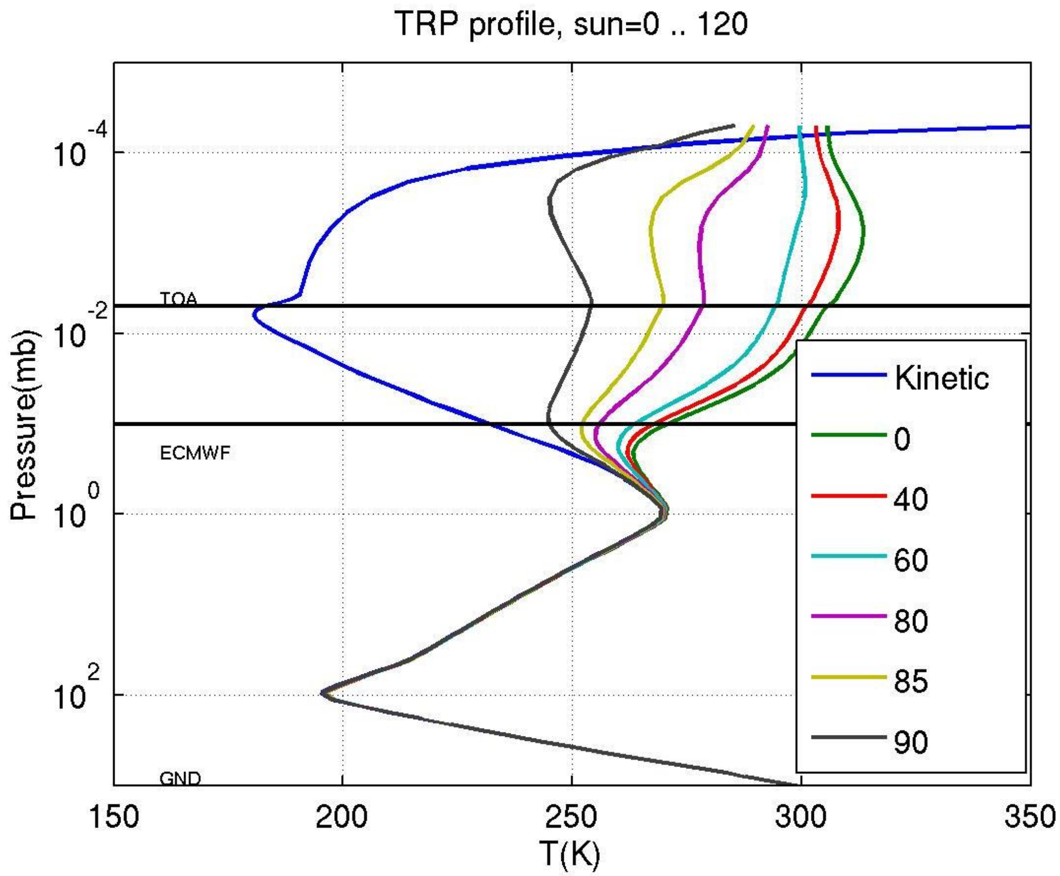
- 10 strong bands (red) weighted towards 2380 cm^{-1} region
- 9 more strong bands (magenta) weighted towards 2200-2340 cm^{-1} region
- Weaker bands (blue) use LTE

NLTE temperatures for tropical profile (sun=0)



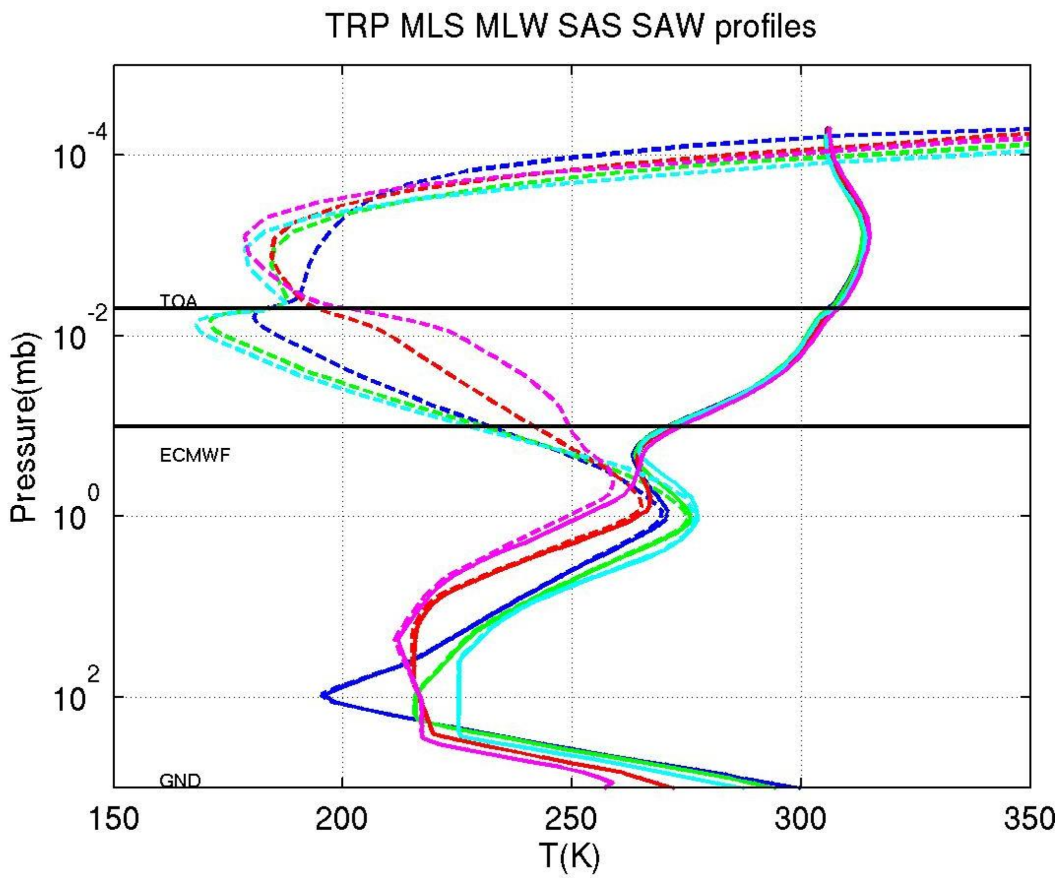
- Current SARTA LTE model based on kCARTA, upto 5e-3 mb
- Current SARTA NLTE model based on kCARTA, upto 3e-5 mb
- ECMWF profiles end at 0.1 mb

Dependance on solar angle (TRP profile, $\Sigma - \Sigma$ band)



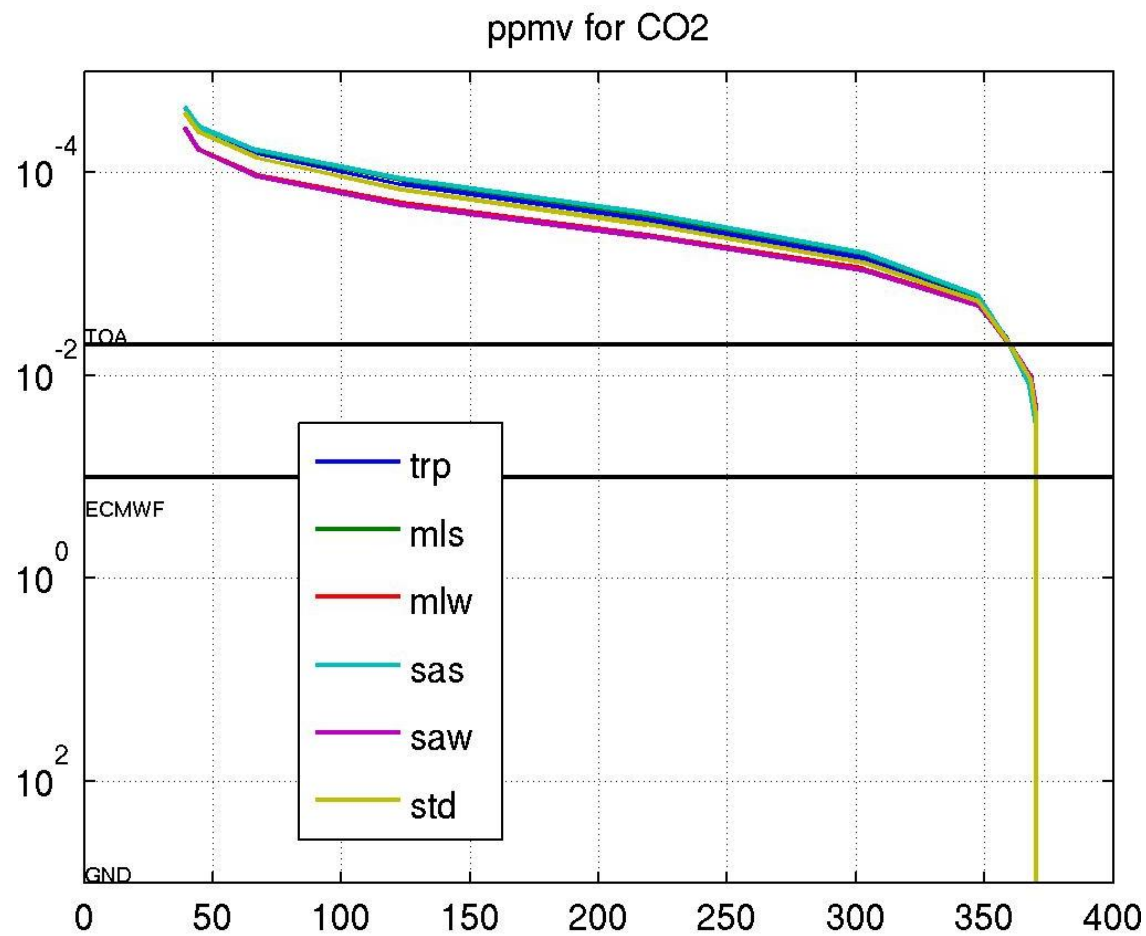
- Current SARTA LTE model based on kCARTA, upto 5e-3 mb
- Current SARTA NLTE model based on kCARTA, upto 3e-5 mb
- ECMWF profiles end at 0.1 mb

Dependance on climatology



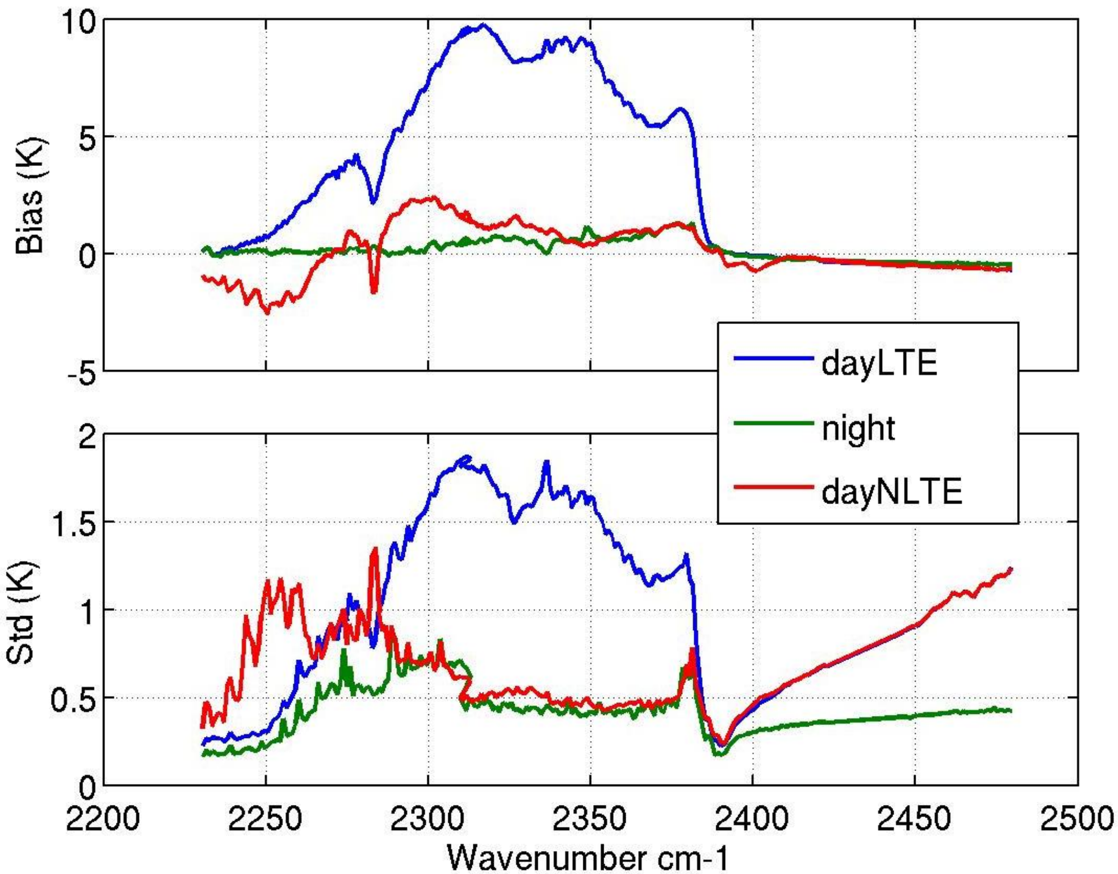
- TRP, MLS, MLW, SAS, SAW used in plots
- Dashed lines are the kinetic (LTE) temperatures
- Solid lines are the NLTE temperatures for the $\Sigma - \Sigma$ band

CO2PPMV : Dependance on climatology



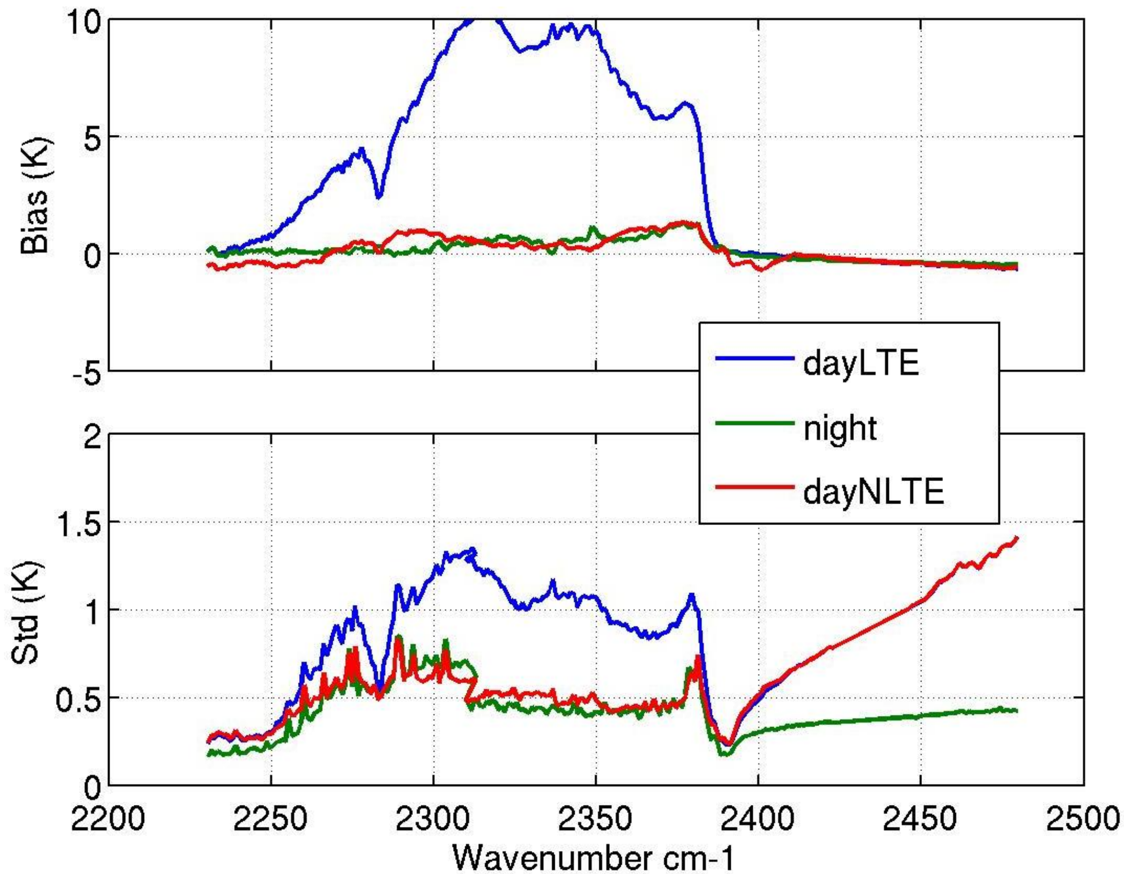
- TRP, MLS, MLW, SAS, SAW, STD used in plots
- STD "splits" the differences

kCARTA 0-120 km results : bias and std



- Arbitrarily selecting day and night profiles from July 25, 2004
- Using orig 10 NLTE bands (large errors in 2200-2340 cm-1)
- About 750 profiles used (kCARTA takes LONG to run!!!)

kCARTA 0-120 km results : bias and std

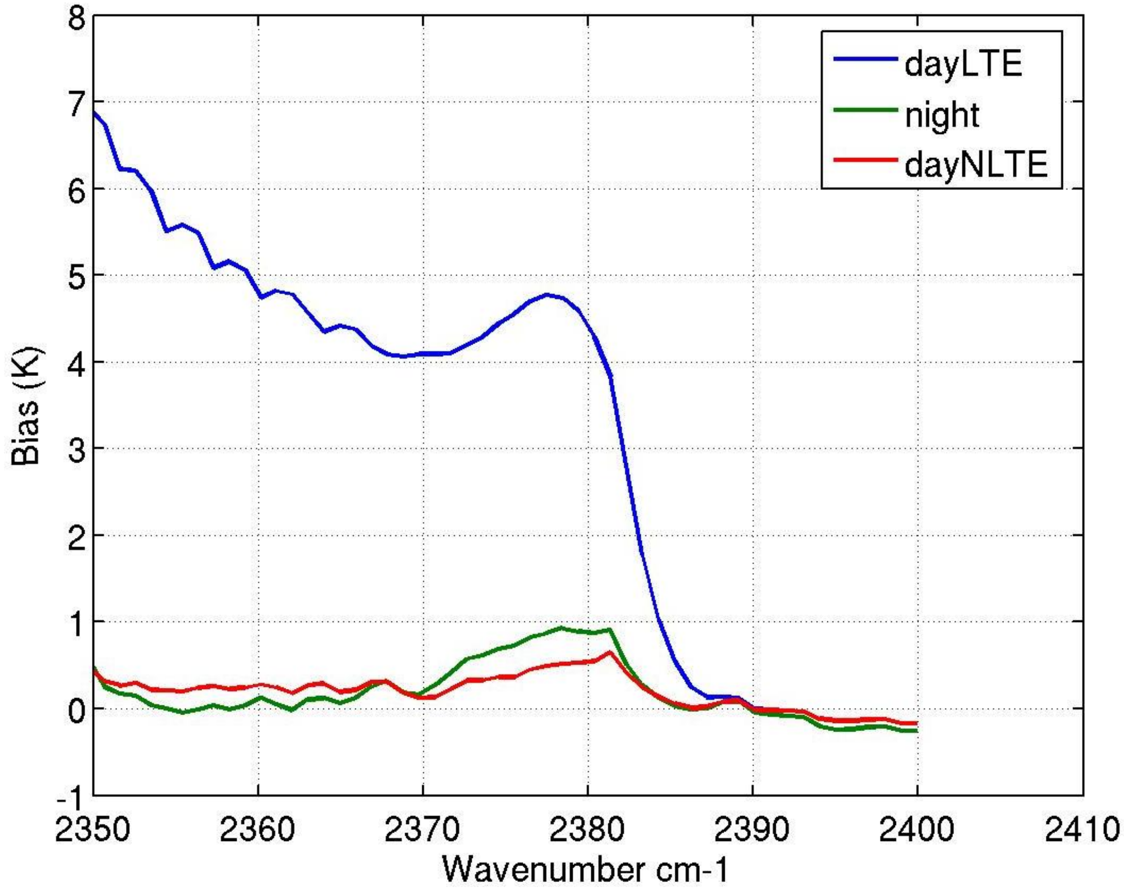


- Arbitrarily selecting day and night profiles from July 25, 2004
- Using the 19 NLTE bands (small errors in 2200-2340 cm-1)
- About 750 profiles used (kCARTA takes even LONGER to run!!!)

NLTE in SARTA

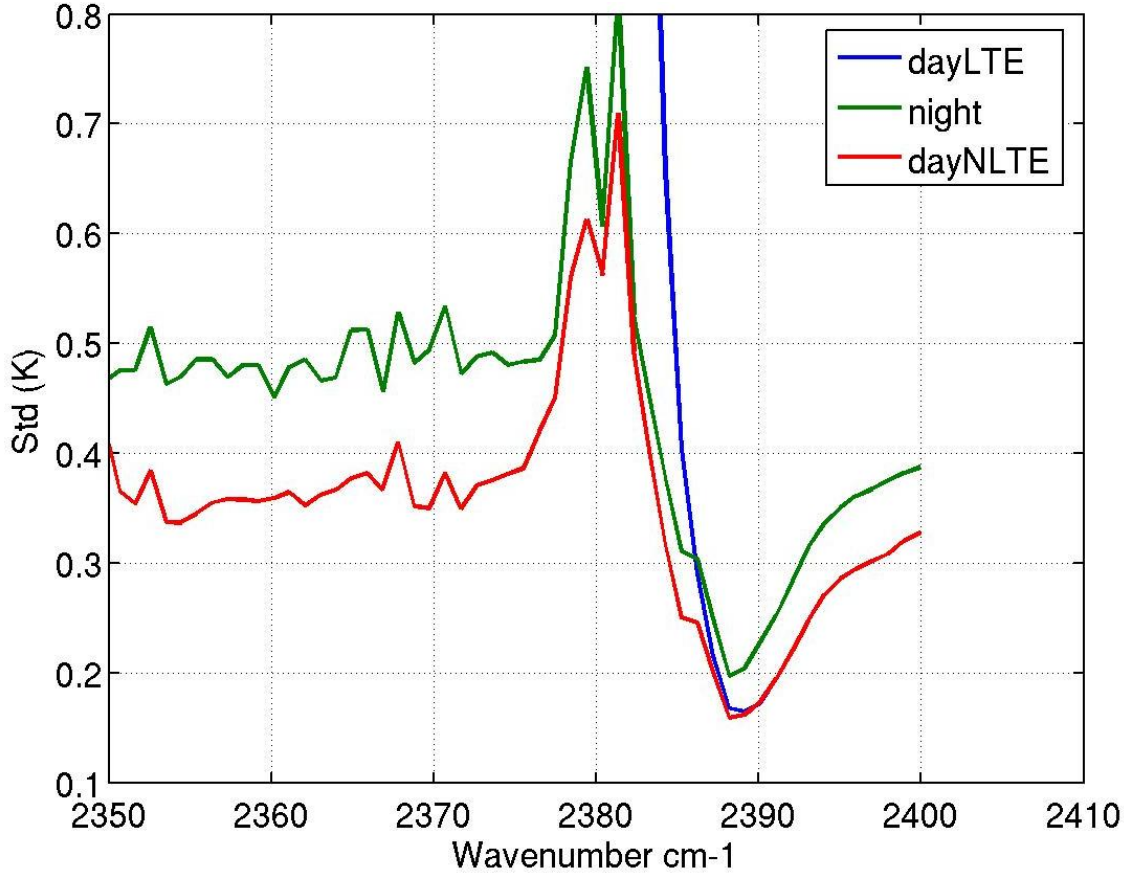
- Upwelling LTE radiance $I_j(lte) = \int SRF_j(\nu) I_{lte}(\nu) d\nu$
- Upwelling NLTE radiance $I_j(nlte) = \int SRF_j(\nu) I_{nlte}(\nu) d\nu$
- Already have SARTA for $I_j(lte)$
- Using kCARTA model $\delta I_j = I_j(nlte) - I_j(lte)$
- Use the predictor-coeff idea : $\mathcal{A}X = \delta I_j$
- Predictors include (a) constant, (b) suncos, (c) suncos^2, (d) suncos $\times Tavtop_5$ (e) suncos at surface

SARTA 0-120 km results : R branchhead



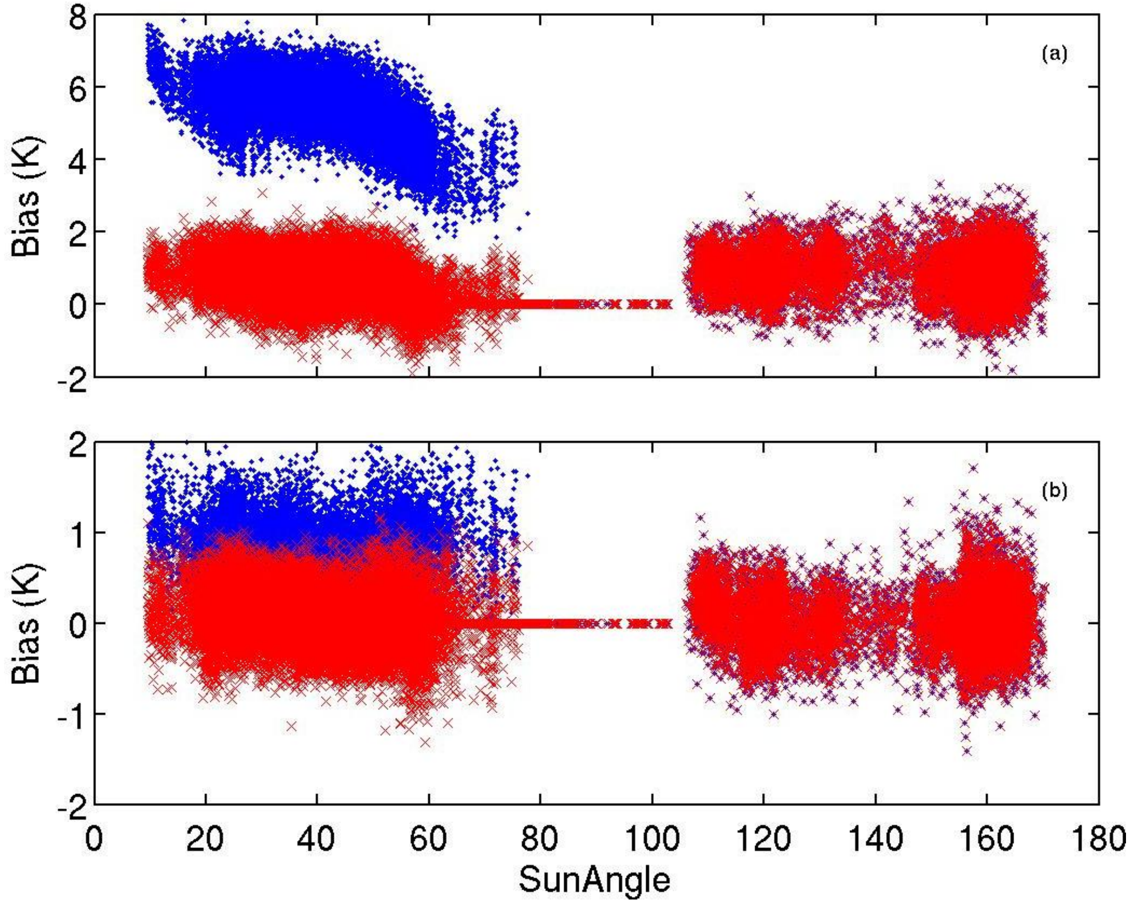
- use the uniform clear profile set (34000 day, 10500 night)
- NLTE biases using OPTIMUM profiles above 0.1 mb

SARTA 0-120 km results : R branchhead



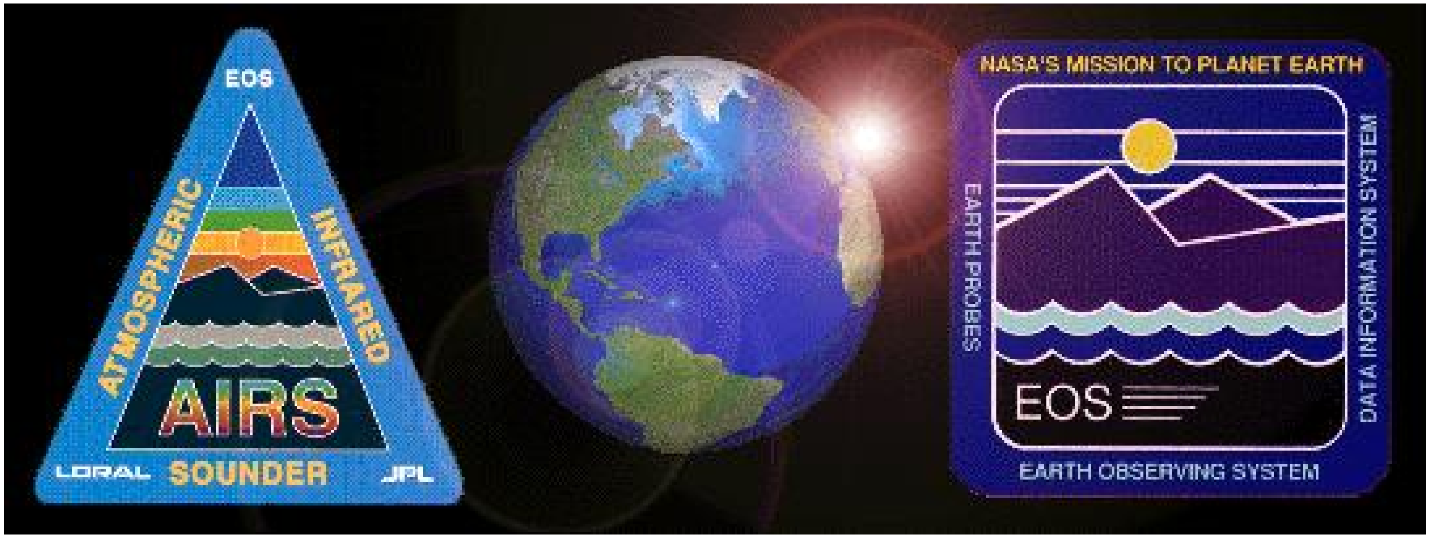
- use the uniform clear profile set (34000 day, 10500 night)
- NLTE stddev using OPTIMUM profiles above 0.1 mb

SARTA 0-120 km results : solzen dependance



- (a) (b) refer to 2380,2385 cm^{-1}; blue = LTE model, red = NLTE model
- use the uniform clear profile set (34000 day, 10500 night)
- NLTE biases using OPTIMUM profiles above 0.1 mb

Work supported by NASA



http://earthobservatory.nasa.gov/
http://www-airs.jpl.nasa.gov/
http://asl.umbc.edu/
sergio@umbc.edu

kTwoStream code (contd)

$$\begin{aligned}
\mu_+ \frac{dI^+}{d\tau} &= -I^+ + \frac{\omega_0}{2}(I^+(1+3g\mu_+\mu_+) + I^-(1-3g\mu_+\mu_+))+ \\
&\quad B_b(1-\omega_0)e^{\beta\tau} + \frac{\omega_0}{4} S_T e^{-(T-\tau)/\mu_{sun})} P(\mu_+, -\mu_{sun})
\end{aligned}$$

$$\begin{aligned}
-\mu_+ \frac{dI^-}{d\tau} &= -I^- + \frac{\omega_0}{2}(I^+(1-3g\mu_+\mu_+) + I^-(1+3g\mu_+\mu_+))+ \\
&\quad B_b(1-\omega_0)e^{\beta\tau} + \frac{\omega_0}{4} S_T e^{-(T-\tau)/\mu_{sun}} P(-\mu_+, -\mu_{sun})
\end{aligned}$$

where we define

μ_+	upgoing stream angle = $+1/sqrt(3)$
μ_-	downgoing stream angle = $-\mu_+$
I^+	upgoing stream intensity
I^-	downgoing stream intensity
τ	optical depth
T	layer total optical depth (0 at bottom, T at top)
ω_0	layer single scattering albedo
g	layer asymmetry factor
B_b	radiance at bottom of layer
S_T	solar radiance at top of layer

$$\begin{pmatrix} I^+ \\ I^- \end{pmatrix} = \begin{pmatrix} R & T^* \\ T & R^* \end{pmatrix} \begin{pmatrix} I_t^- \\ I_b^+ \end{pmatrix} + \begin{pmatrix} E^{up} \\ E^{down} \end{pmatrix} + \begin{pmatrix} F^{up} \\ F^{down} \end{pmatrix}$$

where

I^+	upgoing stream intensity at top of layer
I^-	downgoing stream intensity at bot of layer
$k_\pm$	$\pm 1/\mu_+ \sqrt{(1-\omega_0)(1-\omega_0 g)}$
b	$\frac{1-g}{2}$
α	$\omega_0(1-b)-1$
$a_\pm$	$-(k_\pm + \alpha/\mu_+)\mu_+/(\omega_0 b)$
Δ_0	$-\alpha^2 + (\omega_0 b)^2$
R	$(e^{k_- T} - e^{k_+ T})/\Delta_0$
T	$(a_+ - a_-)/\Delta_0$
R^*	R
T^*	T
E^{up}	$1 - T^*$
E^{down}	$-R$
F^{up}	$-R$
F^{down}	$1 - T^*$

General solution (for $\mu \geq 0$)

$$\mu \frac{dI}{dk} = -I + J\prime(k, I^+(k), I^-(k))$$

where $J\prime(k, I^+(k), I^-(k))$ is the (Eddington's second solution) source function

$$\begin{aligned} J\prime(k, I^+(k), I^-(k)) = & \frac{\omega_0}{2}\left((I^+ + I^-) + 3g\mu\mu_+(I^+ - I^-)\right) \\ & B_b(1-\omega_0)e^{\beta k} + \frac{\omega_0}{4} S_T e^{-(T-k)/\mu_{sun})} P(\mu, -\mu_{sun}) \end{aligned}$$

Since we already know the solutions to the twostream radiances I^+, I^-, this general equation can be exactly solved as well. The solution can be written as

$$I(k,\mu) = \left(I(0,\mu) + S_{up}(k)\right) e^{-k/\mu}$$

Two temperatures!!!

- Sun at 6000K visible wavelengths 400 - 800 nm (0.5 um)
- Earth at 300K infrared wavelengths 3 - 15 um
- $l(um) = 10000/\nu(cm^{-1})$
- Assume radiance = Planck black body = $B(\nu, T)$

$$B(\nu, T) = \frac{2hc^2\nu^3}{exp(hc\nu/K_B T) - 1}$$

$$Units : mWcm^{-2}sr^{-1}/cm^{-1}$$

- Radiance Units $\leftrightarrow$ Temperature